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Prediction of salinity intrusion in the sheltered estuary of Terengganu River in Malaysia using 1-D empirical intrusion model

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Abstract

Generally one dimensional (1-D) empirical salinity intrusion model is limited to natural alluvial estuary. However, this study attempts to investigate its ability to model a sheltered alluvial estuary of the Terengganu River in Malaysia. The constructed breakwater at the mouth of the river shelters the estuary from direct influence of the open sea. The salinity density along the estuary was collected during the wet and dry seasons for scenarios before and after the constructed breakwater. Moreover, the freshwater discharges, tidal elevations and bathymetry data were also measured as model inputs. A good fit was demonstrated between simulated and observed variables, namely salinity distribution and intrusion length for both scenarios. Thus, the results show that 1-D empirical salinity model can be utilized for sheltered estuarine condition at the Terengganu Estuary, but with an appropriate determination of an initial point. Furthermore, it was observed that the salinity intrusion in the study area is largely dependent on the freshwater discharge rather than tidal elevation fluctuations. The scale of the salinity intrusion length in the study area is proportional to the river discharge of the –1/2 power. It was appeared that the two lines of the 1-D empirical salinity model and discharge power based equation fitted well to each other, with the average predicted minimum freshwater discharge of 150 m^3/s is going to be required to maintain acceptable salinity levels during high water slack (HWS) near the water intake station, which is located at 10.63 km from river mouth.

Key words: salinity intrusion, sheltered estuary, freshwater discharge, geometric characteristic, empirical model

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1 Introduction

The salinity intrusion length into the upstream of the estuary is strongly dependent on mixing mechanism in estuaries, which is a function of many factors, such as estuarine shape, tidal behaviour and capacity of freshwater discharge in the estuary (Savenije, 1993; Shaha and Cho, 2009; Zhang et al., 2010). However, freshwater extraction from the river regimes for water supply or agricultural usage, coupled with global warming induced sea level rise (Graas and Savenije, 2008; Ercan et al., 2011), could cause salinity to intrude further upstream (Chen et al., 2016). Salinity intrusion further upstream is a serious issue, as the contaminated freshwater by salt from the sea would render the domestic water supply. Thus, to mitigate the salinity intrusion further upstream, it is important for the water resources manager to regulate the minimum volume of capacity runoff into the estuary (Qiu and Zhu, 2013).

In the present study, the one dimensional (1-D) empirical salinity intrusion model, which was developed by Savenije (1986, 1993, 2005, 2012) is used because of its simplicity and the minimum data required for its inputs (Gisen et al., 2015). The Savenije's empirical salinity intrusion model has been extensively tested in numbers of estuaries around the world (Nguyen et al., 2008; Shaha and Cho, 2009; Gisen et al., 2015), where evidence shows that it can be utilized not only in a single river channel but also in delta estuary of multiple branches (Nguyen et al., 2008). Nevertheless, the model also has some limitations, where Savenije (2012) stated that the empirical salinity intrusion model is still subjected to improvement and it works ideally for natural alluvial estuaries.

The Terengganu Estuary is a sheltered estuary where the constructed breakwater at the river mouth shelters the estuary from direct influence of the open sea, namely South China Sea. Additionally, the man-made reservoir located at the upper stretches of catchment area is regulated by the freshwater runoff capacity in the estuary. The main purposes of this study is: (1) to evaluate the effectiveness of the 1-D empirical salinity intrusion model on the breakwater protected sheltered estuarine at the study site; (2) to examine and compared the performance of the salinity intrusion length by the 1-D empirical salinity intrusion model, with the first order power-law freshwater discharge regression at the study area; and (3) to identify the minimum volume of freshwater discharge required to maintain the acceptable salinity levels at wa-

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ter extraction pump house, which is located at 10.63 km from the river mouth.

2 Study area

The Terengganu Estuary is located at 5.34°N, 103.13°E on the east coast of Peninsular Malaysia, draining into the South China Sea (Fig. 1). The Terengganu River is approximately 65 km in length, with a catchment area of 4 600 km^2. Although it consists of two main tributaries, namely the Terengganu River and the Nerus River, analysis indicated that approximately 90% of the freshwater discharge at the estuary is originated from the Terengganu River. Statistical analysis utilizing 11 years of river gauging data at the Terengganu River (n=94 968) revealed that the mean river discharge equals to 266.20±154.49 m^3/s. A pump house withdrawing water from the Terengganu River for domestic water supply and agricultural purposes is located at approximately 10.63 km from the river mouth. According to National Water Quality Standards for Malaysia, the recommended salinity content for the drinking water is below 0.50×10^{-9}. Nevertheless, the salinity intrusion with the magnitude of saline level 0.10×10^{-9} was observed at the distance of 9.30 km from the river mouth, which could threaten the freshwater withdrawal station if the saline water get intruded further inland. Upper stretches of the Terengganu River is the Kenyir Dam which is a man-made reservoir for hydropower generation, while the river mouth is protected by the breakwater water for navigation purposes (Fig. 1). The breakwater sheltered the river mouth from offshore wave and provides calm conditions at the inner stretches of the river mouth. The tidal regime in this area is dominated by diurnal tide, where in daily the estuary is experiencing one high and one low water, with the mean tidal range is approximately 1.60 m, while the tidal range during the spring and neap tide are 2.40 m and 0.80 m, respectively. It was reported that nearly 80% of the tidal period is low water, which was associated with high volume of freshwater discharge from the upstream (266.20±154.49 m^3/s), together with the mean current speed off 0.13 m/s, resulting to the residence time in the estuary varies approximately from 5 h to 10 h.

3 Background Theories

In this study, the 1-D empirical salinity intrusion model that derived by Savenije (2005) was applied to analyze the longitudinal salinity distributions and intrusion length at the Terengganu Estuary. The 1-D Savenije's empirical model is taken into consideration the relationship between the river runoff and average tidal characteristics, towards the salinity distribution at steady state, namely high water slack (HWS), low water slack (LWS) and tidal average (TA) (Graas and Savenije, 2008; Shaha and Cho, 2009). The exponential function of the estuarine geometry for the bathymetry data surveyed in July 2011 was used in the empirical model to predict the salinity intrusion length, where the geometry equations are written in Eqs (1)–(6) (Savenije, 1993; Nguyen et al., 2012; Gisen et al., 2015). The geometry of the Terengganu Estuary exhibits two segments, namely a short convergence length in the downstream reach near the mouth and a longer convergence distance was observed in the upstream segment (Fig. 2). Therefore, a single exponential function may not be appropriate to represent the geometry of the study site. For this reason, the shape of the Terengganu Estuary could be described by two different exponential functions.

$$A = A_0 \exp\left(-\frac{x}{a_1}\right) \quad \text{for } 0 < x \leqslant x_1, \tag{1}$$

$$A = A_1 \exp\left(-\frac{x - x_1}{a_2}\right) \quad \text{for } x > x_1, \tag{2}$$

$$B = B_0 \exp\left(-\frac{x}{b_1}\right) \quad \text{for } 0 < x \leqslant x_1, \tag{3}$$

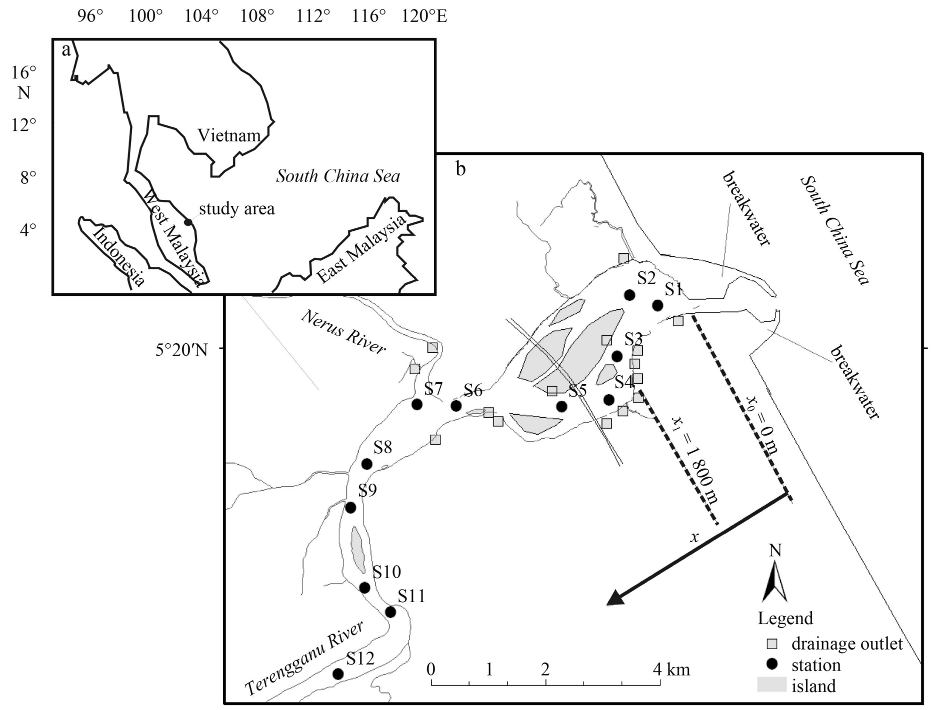

Fig. 1. Map of study area. The solid circles indicate the measured longitudinal salinity stations. The rectangle boxes illustrate the drainage outfall. The distance from the river mouth begin from X_0=0 m.

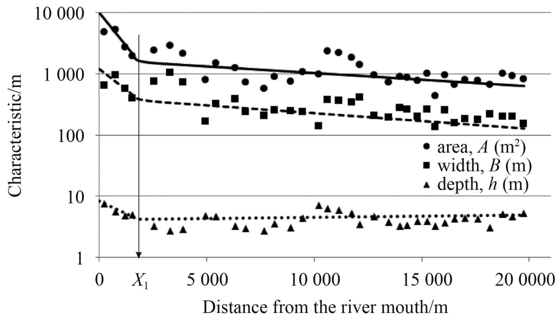

Fig. 2. Cross section area (circles), width (squares) and depth (triangles) of the Terengganu Estuary. X_1 is the cross sectional and width convergence length calculated using Eqs (1) and (6).

$$B = B_1 \exp\left(-\frac{x-x_1}{b_2}\right) \quad \text{for } x > x_1, \tag{4}$$

$$h = h_0 \exp\left(\frac{x\,(a_1-b_1)}{a_1 b_1}\right) \quad \text{for } 0 < x \leqslant x_1, \tag{5}$$

$$h = h_1 \exp\left(\frac{(x-x_1)\,(a_2-b_2)}{a_2 b_2}\right) \quad \text{for } x > x_1, \tag{6}$$

where A, B and h are the cross-sectional area, width and average depth at a distance x from the estuary mouth, respectively (Fig. 1b). A_0, B_0 and h_0 are the initial cross-sectional area, width and average depth at the river mouth that correspond to distance x equilibrium to zero (Fig. 1b), respectively. The parameters a and b represent the cross-sectional area and width convergence length, respectively. Along the longitudinal axis from the river mouth, the distance x_1 is the inflection point (Fig. 2), where it indicates the end stretches of wave affected regions (Gisen et al., 2015). Therefore, the cross-sectional area, width and average depth at the inflection point were rewritten as A_1, B_1 and h_1. In additional, the convergence length at this point switched from a_1 to a_2, while b_1 to b_2.

The dispersion of the longitudinal salinity intrusion length into the upstream is expressed by integrating the geometry Eqs (1)–(6) with the salt balance Eqs (7) and (14). Similar with geometry equations, the salt balance equations also consist of two segments, namely before and after the inflection point. The dispersion and salinity parameters are denoted as D and S, respectively, which is temporal and spatial dependent: depending on the river runoff, tidal range and distance from the river mouth (Graas and Sevenije, 2008; Gisen et al., 2015). D_0 and S_0 represent the initial dispersion and salinity at the estuary mouth, respectively. Meanwhile at the inflection point, the salinity and dispersion are represented by S_1 and D_1, respectively. In order to compute the salinity intrusion length upstream, the freshwater salinity (S_f) should be defined as riverine water salinity, which is close to zero. The β_0 and β_1 are the dispersion reduction rates at the estuary mouth and at the inflection point, respectively, which depend on freshwater discharge, Q_f, dispersion (D) and the Van der Burgh coefficient (K). The Van der Burgh coefficient (K), which ranges between 0 and 1 (Eq. (13)), depends on tidal excursion length (E), H, C, δ and geometry parameters, where H is the tidal range, C the Chezy roughness, and δ the damping rate (detail information refer to Gisen et al., 2015). Tidal excursion length (E), is defined as the net horizontal distance traveled by a water particle from LWS to HWS or vice versa (Savenije, 1989; Jacob et al., 2013), that depends on the T is the tidal period and v_0 velocity amplitude.

$$\frac{S-S_f}{S_0-S_f} = \left(\frac{D}{D_o}\right)^{\frac{1}{K}} \quad \text{for } 0 < x \leqslant x_1, \tag{7}$$

$$\frac{S-S_f}{S_1-S_f} = \left(\frac{D}{D_1}\right)^{\frac{1}{K}} \quad \text{for } x > x_1, \tag{8}$$

where

$$\frac{D}{D_0} = 1 - \beta_0\left(\exp\left(\frac{x}{a_1}\right) - 1\right) \quad \text{for } 0 < x \leqslant x_1, \tag{9}$$

$$\frac{D}{D_1} = 1 - \beta_1\left(\exp\left(\frac{x-x_1}{a_2}\right) - 1\right) \quad \text{for } x > x_1, \tag{10}$$

with

$$\beta_0 = \frac{K a_1 Q_f}{D_0 A_0} \quad \text{for } 0 < x \leqslant x_1, \tag{11}$$

$$\beta_1 = \frac{K a_2 Q_f}{D_1 A_1} \quad \text{for } x > x_1, \tag{12}$$

$$k = 0.2 \times 10^{-3}\left(\frac{E}{H}\right)^{0.65}\left(\frac{E}{C^2}\right)^{0.39}(1-\delta b)^{-2}\left(\frac{b}{a}\right)^{0.85}\left(\frac{Ea}{A_0}\right)^{0.14}, \tag{13}$$

$$E_0 = \frac{v_0 \mathrm{T}}{\pi}. \tag{14}$$

In the 1-D empirical salinity intrusion model, the steady state tidal average (TA) salinity intrusion curve was first derived and salinity intrusions for HWS and LWS were estimated by adding and subtracting the half of the tidal excursion ($E/2$) to the TA salinity intrusion curve, respectively (Graas and Savenije, 2008; Gisen et al., 2015), using the following equation:

$$L^{\mathrm{TA}} = x_1 + a_2 \ln\left(\frac{1}{\beta_1} + 1\right). \tag{15}$$

4 Methodology and data analysis

4.1 *Primary data*

Data collections were conducted during the dry seasons, on July 13, 2011 and July 16, 2012, while the wet season was on March 5, 2012. The measured data during the data collection campaign were: the salinity profiles along the longitudinal axis (S1 to S12) and forty hours diurnal survey on salinity profiles at fixed stations located at the S1 and S9 (Fig. 1b). Additionally, water level and current speed were also measured at the S1 station during the data collection campaigns. Moreover, estuarine bathymetry bed profiles were surveyed during the data collection campaign on July 13, 2011.

Before the salinity measurements were carried out, a unit of water level gauge diver was deployed at the river mouth (jetty located adjacent to S1). The diver was installed during low water to ensure it was submerged in the water even during the lowest tide. A PVC (polyvinyl chloride) pipe with holes was used to hold the diver in place and the pipe was tied to one of the jetty's column. The diver was set to record water level data for each 10 min. Additionally, a unit of current profiler was installed within a stainless steel frame and was deployed at the bed layer to measure current movements at 10 min intervals. The duration of measurement for both the water level and current speed was carried out in a month period during the data campaign in July 2011. However, through the data collection campaign in March and July 2012, the measurement duration was only 40 h.

During high water slack (HWS), longitudinal salinity profiles were measured along the middle stretches of axis using a unit of YSI Professional Plus probe. The probe was equipped with an appropriate weight fixed at its base. Measurements were made at 0.5 m from the water surface and at subsequent depth intervals of 1 m until it reached the bottom layer. The measurements started from the river mouth (x=0 m at Fig. 1b) moving upstream, until the salinity level recorded as low as 1×10^{-10}. During the data collection campaign, the Low Water Slack (LWS) occurred at midnight, thus the longitudinal salinity during the LWS was not able to be measured. In order to determine the salinity condition at the LWS, information from the diurnal survey on salinity at both fixed stations were captured from the data sets. Since the fixed stations located at the river mouth and upper reach of the estuary, two groups of researchers permanently anchored their fibre boats at the measured station and a unit of YSI Professional Plus probe was used to measure an hourly vertical water column salinity distribution.

Bathymetry measurements in the estuary were carried out with a boat equipped with echo sounder and GPS. The bathymetry bed profile was recorded from river mouth to 25 km upstream of the river mouth, which is beyond the final measurement point of the longitudinal salinity.

4.2 *Secondary data*

The salinity intrusion model also requires river discharge information. The freshwater discharge data were obtained from the Department of Irrigation and Drainage (DID), Malaysia, which is the authority in charge for river networks in Malaysia. An automatic river gauge was installed at the Kpg Tanggol station by DID, which is approximately 28 km from the river mouth. The freshwater discharge rates for maximum, average and minimum at the Kpg Tanggol gauging station were recorded as 2 808 m^3/s, 266 m^3/s and 21 m^3/s, respectively.

The secondary longitudinal salinity levels were obtained from DID that were measured during dry season in the year 1975, which was before the construction of the Kenyir Dam at the upper stretches and breakwater groins at the downstream. The bathymetry condition reported in the DID report (1975) illustrated the navigation channel depth, width and shape were almost similar with primary bathymetry measurement in July 2011. Therefore, as limited bathymetry information data in the year 1975, the cross-section magnitude of area, width and mean depth measured in July 2011 was used to estimate the salinity intrusion lengths for scenario before and after the constructed breakwater.

4.3 *Model performance*

The performance of the model in predicting the salinity level and intrusion length in the estuary was done by evaluating the correlation between the computed results and measured data. In this study, the degree of accuracy for the predicted model was defined by root mean square error (E_{RMS}) and Nash-Sutcliffe efficiency (E_{NS}). The equations used to perform the analysis are listed as below:

$$E_{\rm RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}, \qquad (16)$$

$$E_{\rm NS} = 1 - \frac{\sum\limits_{i=1} (P_i - O_i)^2}{\sum\limits_{i=1} (O_i - \bar{O}_i)^2}, \qquad (17)$$

where P_i is the predicted value at a certain point of estuary by using salinity intrusion model, O_i is the observed value from the measurement and $\bar{O}_i$ is the average of observed values. In order to investigate the predominant factors in controlling the salinity intrusion in the Terengganu Estuary, the regression coefficient of R^2 was used to identify the importance of freshwater discharges and tidal fluctuations on the salinity intrusion length.

5 Results and discussion

5.1 *Geometry of the estuary*

The magnitudes of the cross-sectional area and width were defined from July 2011 bathymetry data on the tidally averaged steady state, whereas the water depth was obtained from the ratio of the area to the width. The geometry analysis were computed by Eqs (1)–(6) and they fitted well with the measured data (Fig. 2), which means it follows an exponential function. Through the geometry, tidal excursion and salinity intrusion length analysis, it was identified that the initial point of river mouth (X_0=0 m) was located at the inner stretch of the estuary as shown in Fig. 1. The shape analysis illustrated that the estuary consisted of two width and cross-sectional lengths as a_1, a_2, b_1 and b_2 (Table 1), with the inflection point located at 1.80 km from the estuary mouth (Fig. 1). The inlet of the estuary is protected by breakwater groins and tended to result the waves to propagate only through the navigation channels, where it has been evidenced the inflection point is located at the end reach of navigation route. Previous study (Gisen et al., 2015) on the six natural alluvial estuaries in Malaysia, reported all the estuaries also appeared to consist of two width and cross-sectional convergence length. Gisen et al. (2015) highlighted that estuaries that do not experience strong ocean waves near the river mouth generally can be described by a single reach. However, evidence from the site also indicates that deeper navigation channel at the lower stretches of the river mouth and irregular shape of the river mouth might be contributed to the two reaches of convergence length in the study area.

5.2 *Longitudinal variation in salinity*

The longitudinal transect salinity structure reflects the strong

Table 1. The geometric conditions at the Terengganu Estuary

Variables	Unit	Symbol	Value
Area at the mouth	m^2	A_0	10 000
Area at X_1	m^2	A_1	1 700
Cross sectional convergence length 1	m	a_1	1 000
Cross sectional convergence length 2	m	a_2	20 000
Width at the mouth	m	B_o	1 200
Width at X_1	m	B_1	410
Width convergence length 1	m	b_1	1 600
Width convergence length 2	m	b_2	17 000
Inflection point	m	X_1	1 800
Depth initial	m	h_0	8.33
Depth at X_1	m	h_1	4.24

stratification conditions observed in the Terengganu Estuary during both wet and dry seasons (Figs 3a and b). By the end of the wet season in early March 2012 (Tangang et al., 2012), fresh water occupies the middle stretches of the estuary where excessive freshwater volumes restricted seawater to the lower portion of the estuary, with salinity intrusion reached only 7.01 km upstream from the river mouth. Meanwhile, during the dry season (July 2012), lower rainfall reduced river runoff and allowed saline water to travel further upstream. Figure 3b reveals that saline water intruded 10.14 km from the river mouth during the study period. However, the general salinity structure in both seasons suggested that the estuary is subject to salt-wedge conditions.

In a salt-wedge estuary, a high volume of fresh water generally occupies surface layers and saltier seawater intrudes into the estuary through the bottom layers of the water column (Dyer, 1997; Kasai et al., 2010). The ratio of the salinity difference between surface and bottom layers (∂*S*) divided by the depth-averaged salinity (<*S*>) shown in Fig. 3c represents the stratification parameter (∂*S*/<*S*>) of the estuary. During both seasons, the value of this stratification parameter was greater than 0.32, indicating strongly stratified conditions, i.e, those characteristic of a salt-wedge estuary (Hansen and Rattray Jr, 1966; Shaha and Cho, 2009; Jacob et al., 2013). Moreover, a higher value developed during the wet season than the dry season, consistent with the salinity structures shown in Figs 3a and b.

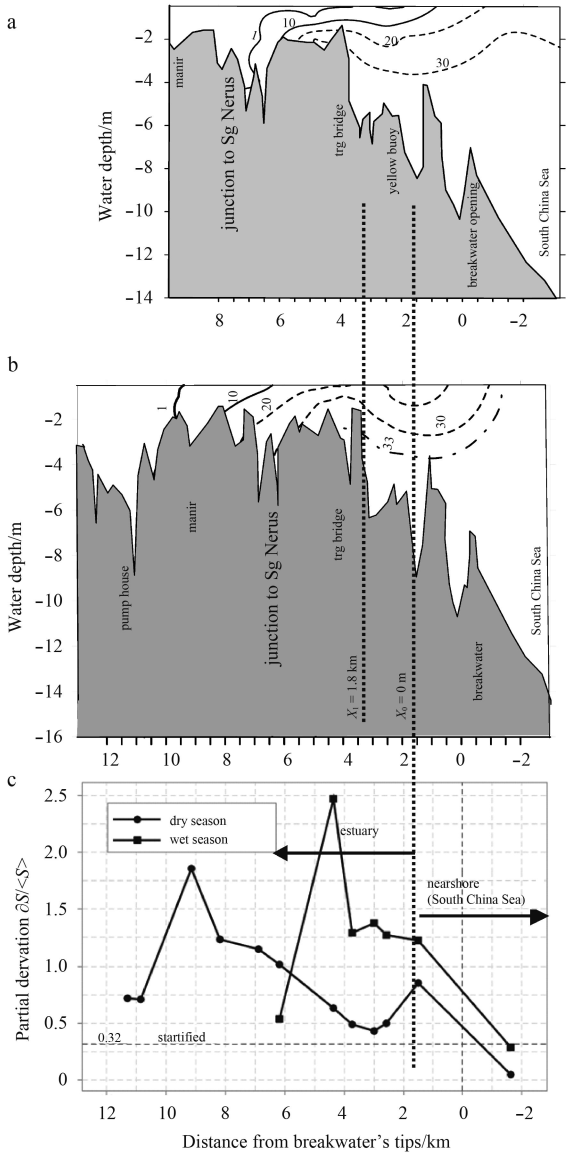

Fig. 3. Longitudinal distribution of salinity intrusion at HWS during the wet season (a) and dry season (b). Salinity stratification plot (c) indicating δ*S*/<*S*> greater than 0.32, representing stratified estuary conditions.

5.3 *Salinity analysis*

On the basis of geometric parameters, the longitudinal salinity intrusion length along the river estuary was computed using Eqs (7)–(15). The Van der Burgh coefficient *K* and dispersion D_0 were calibrated in order to obtain the best fit between the simulated salinity intrusion length and the observed salinity measurements. In applying the 1-D empirical model, K, E_o, D_o, Q_f and S_o were the main calibration parameters. The salinity intrusion lengths were calculated using *T* equals to 24 h (86 400 s), as the study site is experiencing diurnal tide. It was observed that during spring tide, the initial tidal velocity at the river mouth (v_o) varied from 0.25 m/s to 0.35 m/s, while during neap tide the v_o ranged from 0.10 m/s to 0.20 m/s. The estimation of the intrusion length was performed based on tidal average (TA) model, while for the HWS and LWS the values were computed on half of the tidal excursion ($E_0/2$) that added and subtracted to the TA model, respectively (Savenije, 1993, 2005). Results of the salinity intrusion length computed from the analytical model are plotted in Fig. 4 and it appeared the intrusion length generally fitted well with the measured data.

It is noticeable during the HWS (Fig. 4c), the salinity level at the river mouth (S1 and S2) was lesser than the middle stretches of estuary (S3 and S4). Perhaps it might be due to horizontal circulation flow, where the freshwater flow into the river mouth drains from the left hand side (Fig. 1b) (Dyer, 1997, p 20). Effluent discharge from a unit of drainage outlet located at the upper reach of Sta. S2 is directed into the estuary with the capacity of 2.98 m^3/s (Fig. 1b). Therefore, the freshwater runoff might dilute the saline water and reduce the salinity at the river mouth and produce a remarkable lesser salinity compared to the adjacent downstream salinity levels. Meanwhile in Stas S5 and S6, which were located nearby to main drainage outlets (DID, 2010; Fig. 1b), the runoff from the main drain might reduce the salinity at these stations through dilution processes. It was observed that under this scenario (Table 2, case July 2012), the magnitude of observed freshwater discharge, tidal range and salinity intrusion length were 157.00 m^3/s, 2.10 m and 10.14 km, respectively. The predicted salinity intrusion length by 1-D empirical model was 10.62 km from the river mouth, which was approximately 4.73% different from actual measurement. Furthermore, the root means square error (E_{RMS}) on the longitudinal salinity density was 1.52×10^{-9}, which was approximately 9.44% of the average salinity. It is clear in the results that the 1-D empirical model has a very good fit for the study site, which the errors were less than 10% from the measured data.

As mentioned in the methodology and data analysis section, the LWS data was captured from fixed stations due to difficulty to measure the data during midnight. The projected LWS salinity intrusion length by the analytical model fitted well with the measured LWS. It was observed that during the LWS, there was almost zero salt content in the longitudinal water columns, where the entire estuary behaves almost like a river (Figs 4a–c). This can be explained by the huge volume of freshwater dis-

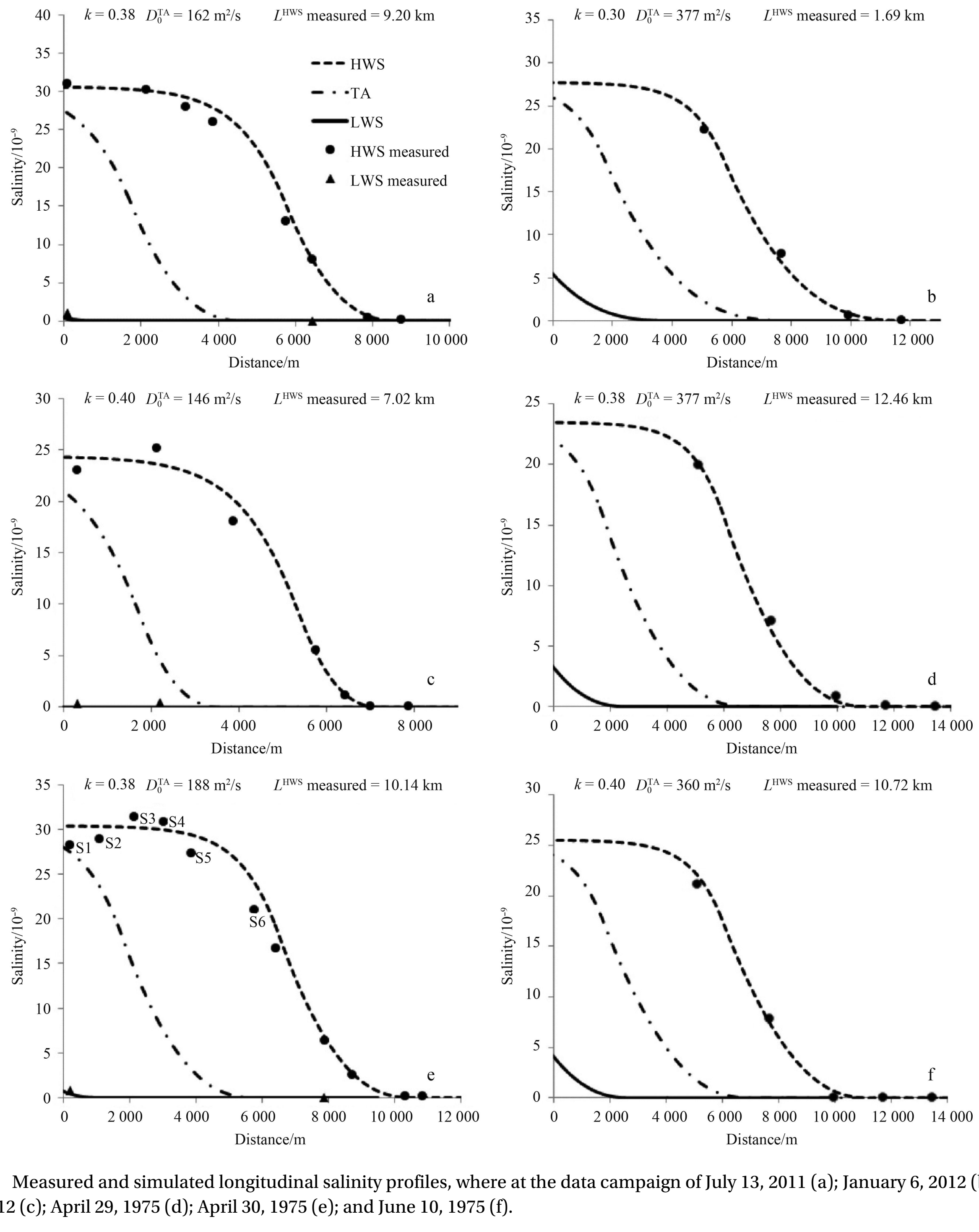

Fig. 4. Measured and simulated longitudinal salinity profiles, where at the data campaign of July 13, 2011 (a); January 6, 2012 (b); July 16, 2012 (c); April 29, 1975 (d); April 30, 1975 (e); and June 10, 1975 (f).

charge from upstream associated with longer ebb tide duration, which was approximately 80% (19 h) of the daily tidal period, which have been diluted and transported out all saline water in the estuary into the nearshore water bodies (Phillips, 1985).

The estimated salinity intrusion length for the condition prior to the construction of the man-made structures, namely the Kenyir dam at the upper stream of catchment and nearshore breakwater at the river mouth, presents a good agreement with the measured data (Figs 4d–f). As evidence, it was shown that the salinity intrusion analytical model works well in natural alluvial estuary as stated by Savenije (2012). The result shows that the regulated freshwater discharge after the constructed Kenyir dam (Fig. 5) reduced the salinity intrusion length further inland, with the shorter intrusion length between Figs 4a–c (after the reservoir scenario) compared to Figs 4d–f (before the reservoir scenario). The averages measured salinity intrusion length before and after the constructed reservoir upstream were 9.86 km and 8.78 km, respectively. The similar scenario is reported after the completion of Three Gorges Reservoir, where salinity water intrusion becomes weaker in the estuary when water is released during the dry season (Qiu and Zhu, 2013). The performance of the empirical model before and after the constructed breakwater at the river mouth was tabulated in Table 2. This finding supports well with findings made by Savenije (2012) that the typical length of the sa-

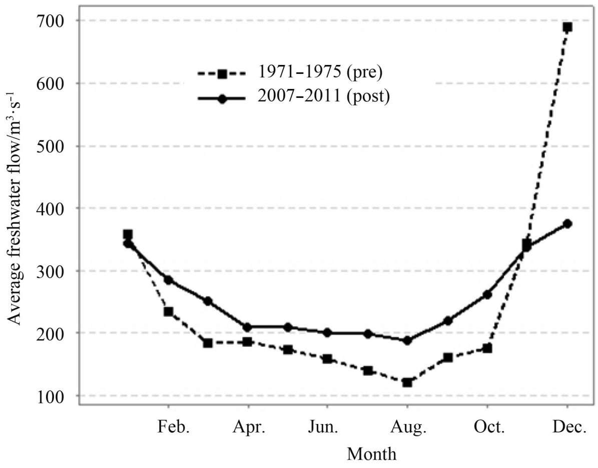

Fig. 5. Comparison on average five years flow before (pre) and after (post) the constructed dam at the upstream.

linity intrusion length for a diurnal tide estuary is approximately 10.00 km. Previous study in the peninsular region of Maipo River in Chile, which experienced mixed diurnal tide, indicates salinity intrusion of 12.00 km upstream of the river mouth (Piñones et al., 2005). It was also observed that during the HWS (Fig. 4), the study area was experienced higher concentration of the salinity level at the river mouth (Figs 4a–c) for the period of the year 2011–2012 compared to the year 1975 (Figs 4d–f). According to Ercan et al. (2011), this study area experienced sea level rise with the magnitude of 0.22 cm/a. Analysis by Bhuiyan and Dutta (2012), documented that 1.00 m sea level rise is able to increase 1.50×10^{-9} of salinity density in the Gorai river network in Bangladesh. Therefore, the higher concentration of salinity densities in the current years (2011–2012) at the study area might be effected by sea level rise.

Through the 1-D empirical salt intrusion model, it was simulated the average calibrated value for the Van der Burgh (K) coefficient was 0.36, while the dispersion coefficient (D_0) was 178.22 m^2/s (Table 2). If compared with the predicted value calculated from Eqs (13) and (21) refer to Gisen et al. (2015), the K and D_0 were 0.32 and 100.81 m^2/s, respectively. According to Shaha and Cho (2011), values of the K ranging from 0.3 to 0.8 would mean that both tide and density are important variables for the mixing processes in the estuary. Moreover, for six others estuaries in the Peninsular Malaysia, the dispersion coefficient was reported ranging from 41.00 to 601.00 m^2/s, while the K value varies from 0.20 to 0.40 (Gisen et al., 2015). Hence, the mixing processes by both tide and discharge, associated with freshwater inputs into the Terengganu River estuary, resulting to the dispersion coefficient in the estuary to vary from 88.00 to 383.00 m^2/s (Table 2).

5.4 *Performance of the empirical model*

The performance of the analytical models in simulating the salinity intrusion in the estuary was evaluated by comparing the computed and predicted result at the study area. The accuracy model was defined by the E_{RMS}. It was determined that the E_{RMS} of the water salinity was 1.17×10^{-9} and 0.29×10^{-9} which correspond to 6.98% and 7.09% of the average salinity for the scenario of after and before the construction of the breakwater, respectively. Meanwhile for the salinity intrusion length, the E_{RMS} values after and before the installation of the breakwater was 398.33 m and 357.00 m, respectively. These correspond to about 4.54% and 3.62% different from the average intrusion length (Table 2). The results indicated that the analytical model predicts better for salinity intrusion with lower percentage of error (less than 5%) compared to salinity distribution (less than 10%). This suggests that the analytical salt model is reasonably reliable and efficient in simulating the salinity level in Terengganu River estuary, with either in the condition of natural or sheltered alluvial estuary. Similar condition has been reported by Gisen et al. (2015) on the other natural alluvial estuaries in Peninsular Malaysia, where the E_{RMS} results on the salinity distribution along the estuary obtained ranging between 0.83×10^{-9} and 1.81×10^{-9}, which was below 10% of the average salinity.

The performance of the analytical models in simulating the salinity levels and intrusion length in the estuary can be evaluated by the Nash-Sutcliffe efficiency (E_{NS}). The E_{NS} for the salinity levels illustrated almost all the values are near to unity (Table 2), ranging from 0.92 to 1.00. This means the empirical model is very reliable and efficient in simulating the salinity levels. The av-

Table 2. Results of the salinity intrusion length as measured (A) and predicted (B) by the salinity curve at the type conditions

Period	Type	A: Measured intrusion length/m	B: Predicted intrusion length/m	K	D_0^{TA} (calibrated)/ $m^2 \cdot s^{-1}$	$Q/m^3 \cdot s^{-1}$	Tidal/m	E_{RMS} salinity/ 10^{-9}	E_{RMS} intrusion length/m	E_{NS} salinity	E_{NS} intrusion length
7/13/2011	1	9 198.00	8 741.00	0.38	162.00	150.00	2.00	0.81	457.00	0.99	–0.20
3/5/2012	1	7 010.00	7 268.00	0.40	146.00	224.00	2.12	1.19	258.00	0.98	0.98
7/16/2012	1	10 136.00	10 616.00	0.38	188.00	157.00	2.10	1.52	480.00	0.95	0.87
Average after B/W		8 781.33	8 875.00	0.39	165.33			1.17	398.33	0.97	0.55
4/29/1975	2	11 694.00	12 271.00	0.30	338.00	133.00	2.16	0.56	577.00	0.92	0.90
4/30/1975	2	12 461.00	12 245.00	0.35	383.00	103.00	2.16	0.39	216.00	0.98	0.99
5/14/1975	2	9 610.00	9 835.00	0.20	93.00	133.00	2.16	0.37	225.00	0.99	0.18
5/28/1975	2	9 766.00	9 924.00	0.30	106.00	133.00	2.36	0.18	158.00	1.00	–1.91
6/10/1975	2	10 721.00	10 941.00	0.43	382.00	118.00	2.16	0.57	220.00	0.97	0.93
6/12/1975	2	8 279.00	8 476.00	0.35	96.00	148.00	2.36	0.13	197.00	1.00	0.98
7/9/1975	2	8 102.00	8 001.00	0.38	110.00	170.00	2.16	0.26	101.00	0.99	1.00
7/10/1975	2	8 150.00	8 692.00	0.30	88.00	135.00	2.16	0.24	542.00	0.99	0.90
7/23/1975	2	9 944.00	9 896.00	0.40	124.00	103.00	1.96	0.46	48.00	0.97	0.68
Average before B/W		9 858.56	10 031.22	0.33	191.11			0.29	357	0.98	0.52

Note: 1 indicates after constructed breakwater (B/W), 2 presents before constructed breakwater. K is Calibrated Van der Burgh coefficient, D_0 the dispersion coefficient at tidal average, Q fresh water discharge, tidal range (m). The model performance is in terms of root mean square error (E_{RMS}) and Nash-Sutcliffe efficiency (E_{NS}) for salinity and intrusion length (L_{HWS}).

erage value of E_{NS} on the salinity intrusion length is approximately 0.54 (Table 2), indicates that the model predictions are as accurate as the mean of the observed data. As the conclusion, the empirical model is reliable model to predict salinity levels as well as intrusion lengths, either for natural alluvial estuary or sheltered estuary in the Terengganu Estuary.

5.5 *Dominant factors controlling salinity intrusion length*

It is important to determine either the freshwater buoyancy or tidal range predominantly controls the salinity intrusion in the study estuary. The magnitude of salinity intrusion length for study area was found to be proportional to the discharge of approximately $-\frac{1}{2}$ powers, with the R-squared value is 0.63, which is considered a good fit of the line to the data (Fig. 6a). Meanwhile the linear relationship found to be poorly related between tidal range and the intrusion length, with the R-squared value of 0.01 (Fig. 6b). The poor relationship between the tidal range and salinity intrusion length is perhaps the distance of salinity intrusion length is located at the most upper stretches of the estuary, where freshwater discharge normally plays an important role in adjusting the characteristics of upper stretches zone of the estuary. The regression fitting indicated that the salinity intrusion length was greatly dependent on the river discharge but to a lesser extent on the tidal surface elevation, as depicted by the greater R-squared value. Similar finding was reported by Zhou et al. (2012) at the Zhujiang Estuary in China, where it was defined that the freshwater runoff was a dominant factor to the saltwater intrusion and salinity structure profiles in the estuary.

Under the steady state conditions, Monismith et al. (2002) highlighted the salt water intrusion length scale (L) is described by the power-law regression of the river discharge as shown by Eq. (18):

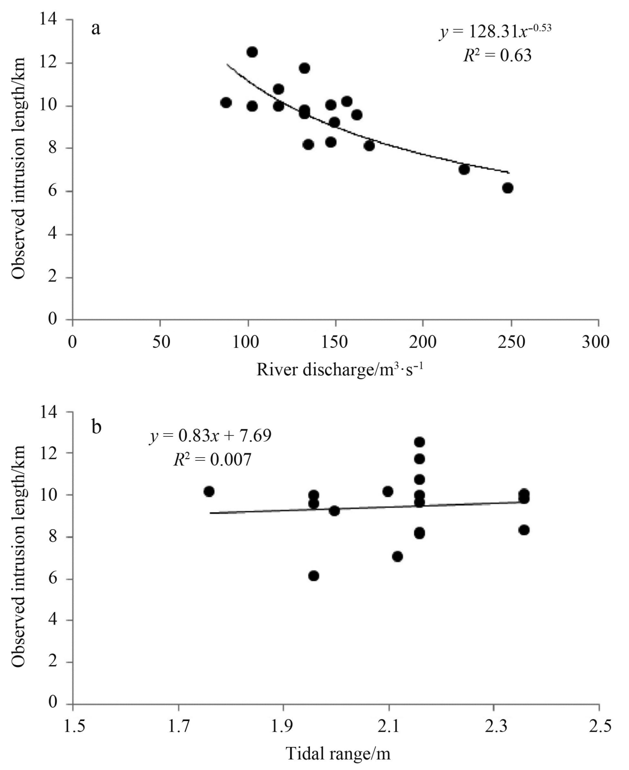

Fig. 6. The best fit line for measured salt intrusion lengths with the freshwater discharge (a) and tidal range (b) in the study area.

$$L \approx Q^{\alpha}, \tag{18}$$

where α is the power dependence coefficient and varies widely under different conditions that depend on geometry and stratification of water column and vertical mixing. This equation is supported well by Brockway et al. (2006), Sun et al. (2009) and Becker et al. (2010) on the negative relationship between salinity intrusion length and freshwater discharge. The α varies between –1/7 and –1/3 power of runoff in the northern San Francisco Bay and Cape Fear Estuary (Monismith et al., 2002; Becker et al., 2010), respectively. While for the Hudson and Sumjin Estuaries is reported as –1/5 powers based of discharge (Shaha and Cho, 2009). However, the current study shows that the alpha is having approximately –1/2 powers to freshwater discharge, with the regression equation as written in Eq. (19). According to Monismith et al. (2002), the standard power-law regression with –1/3 indicated that the upstream salt flux associated with gravitational circulation is more sensitive to the longitudinal salinity gradient. Perhaps, the study area is experiencing diurnal tide, where approximately 80% of the tidal period is ebb tide, this associated with high freshwater discharge released from the upstream Kenyir Dam, which has enhanced the longitudinal salinity gradients at the upper stretches of the estuary.

$$L = 128.31Q^{-0.53}. \tag{19}$$

5.6 *Salinity intrusion*

The salinity intrusion length at HWS was computed using the analytical model as presented in Eq. (15). The magnitudes of the K and D_0 used in the equation were based on the average calibrated value as tabulated in Table 2, which correspond to 0.36 and 178.22 m²/s, respectively. The fitted line for the salinity intrusion length established from different discharge capacities was plotted in Fig. 7 (solid line). The regression fitted line for discharges related to salinity intrusion lengths by using the power-law regression Eq. (19) was also plotted in Fig. 7 (solid dotted line). Both lines appear almost similar to each other; however at the same distance of salinity intrusion length the discharge estimated by the 1-D empirical salinity intrusion model was comparatively higher compared to power-law discharge regression output. It illustrates the minimum amount of freshwater discharge; approximately 110.00 and 150.00 m³/s is required by power-law regression and 1-D empirical model, respectively (Fig. 7), to maintain the acceptable salinity levels at the water intake station that is located at 10.63 km from the river mouth (Pulau Musang pump house). It is probably due to comprehensive data input on the empirical model equation, such as geometrical conditions, dispersion and mixing coefficients and other physical variables, which might contribute to high volume of discharge requirement compared to power-law regression equation. It was evidenced in the Table 2 for the data captured in July 2012, the freshwater discharge with the magnitude of 157.00 m³/s derived the salinity intrusion length to the distance of 10.14 km from the river mouth, with the high accuracy coefficient of E_{NS} equal to 0.87. Therefore, it can be concluded that the minimum freshwater discharge of 150 m³/s will require to maintain an acceptable salinity levels during HWS near the water intake station located at 10.63 km from river mouth. However, the actual freshwater discharge at the upstream from the water intake has to be higher, since this minimum discharge does not take into consideration of the volume of water extraction at the pump house for domestic and agricultural purposes.

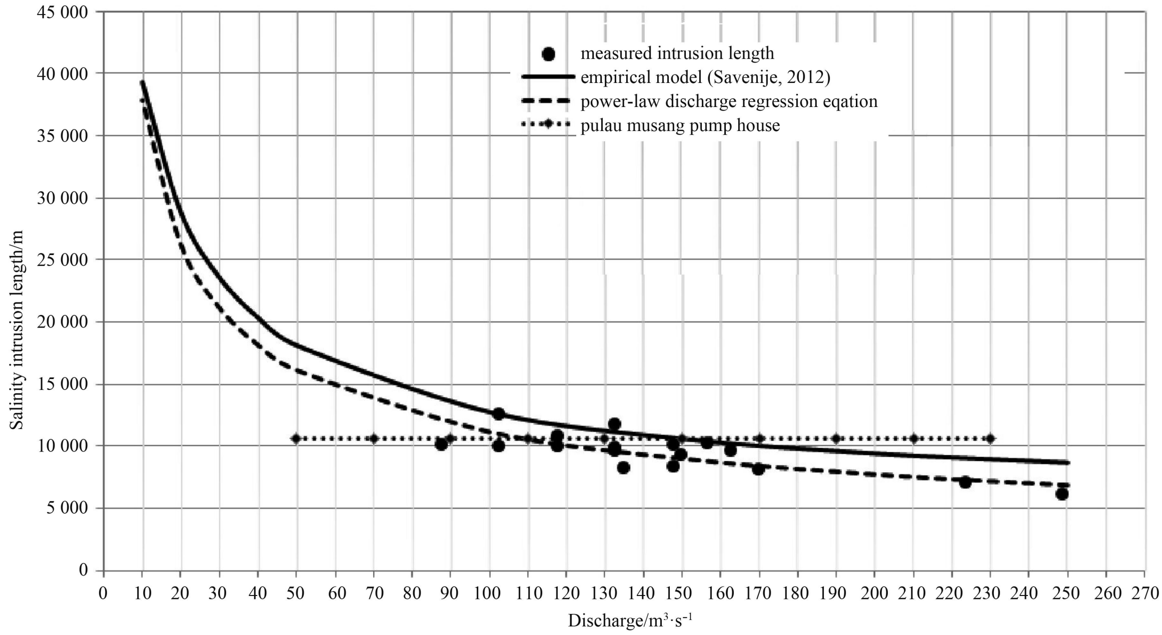

Fig. 7. Comparison on predicted freshwater discharge related with salinity intrusion length using empirical model and discharge power-base regression.

6 Conclusion

The 1-D empirical salinity intrusion model is not only applicable to natural estuary condition, but also appears to perform well under the sheltered estuary. It shows that the 1-D empirical salinity intrusion model is reliable model to predict both salinity intrusion lengths as well as salinity distribution levels, with acceptable low percentages of error compared to measured data. It was defined that river discharge was the predominant control on the salinity intrusion length in the study area rather than spring-neap tidal oscillation. The computed fitted lines simulated by 1-D empirical salinity intrusion model and first order power-law discharge regression, have demonstrated fairly similar trend of curve. Nevertheless, at the same salinity intrusion level the discharges computed by 1-D empirical salinity intrusion model was comparatively higher compared to power-law discharge regression output. It was predicted that the minimum amount of freshwater discharge required to maintain acceptable salinity level at the freshwater intake station was approximately 150.00 m^3/s calculated by 1-D empirical model.

This study provides useful information on the salinity intrusion for water resources managers in understanding amount of minimum freshwater discharge needed to maintain an acceptable salinity levels during HWS near the water intake station. However, it should also be noted that human interference such as freshwater extraction and sand dredging activities will increase the salinity intrusion length to intrude further inland. Therefore, it is suggested that the water resources authorities should consider regulating both water extraction and dredging activities to avoid severe salinity intrusion problems into the upper stretches of the estuary.

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